GLEEM – A NEW COMPOSITE GUN TUBE PROCESSING TECHNOLOGY

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ABSTRACT

The development of a process to emplace a refractory metal liner inside a gun tube is described. The process consists of filling the liner with an elastomeric material and then slipping this arrangement into the gun tube. The ends of the liner are plugged with plastic disks and pressure is applied to the elastomeric material by a load frame. The original clearance between the liner and gun tube is small, so the action of the pressure expands the liner slightly until it contacts the steel gun tube wall. At that point, greater pressure can produce residual internal stresses within the steel gun tube. Pressures in excess of 250 ksi have been achieved with this simple arrangement. The stresses provide an autofrettage to the steel tube as well as forces retaining the liner inside the tube. Initial efforts have resulted in bond strengths over 3 ksi. In addition, by tailoring the degree of lubrication between the elastomeric material and the liner, a graded autofrettage can be produced in the steel gun tube.

1. INTRODUCTION

The United States Army uses liners or coatings in many of its guns currently in service. This includes a chrome coating in the M256 main tank armament, a nitride surface treatment in the M242 Bushmaster medium caliber canon, and a Stellite 21 liner in the M2 machine gun. The liners or coatings increase the barrel wear life by protecting them against the effects of hot propellant gasses. Chrome coatings are applied by electro-plating the bore of the gun, whereas the Stellite liner is mechanically emplaced. Recent advances have raised the possibility of explosively bonding liners to gun tubes [Lowey, 2002; de Rosset, 2006]. In addition, a program is being conducted by Benet Laboratories to develop a tantalum sputtering process to line the M256 main tank gun. The choice of liner or coating material, as well as the means by which the coating or liner is applied, is highly dependent on the cost savings achieved through extended barrel wear life.

A new idea that has potential to apply liners to gun tubes economically has been proposed in a recent patent disclosure [Carter and de Rosset, 2008]. The idea, whose genesis was in pressure testing of ceramic tubes [Carter, 2006], is to use an elastomeric material to apply pressure to the liner and force a mechanical bond between it and the gun bore. The term "Gun Liner Emplacement by Elastomeric Material" or GLEEM has been coined for this process. GLEEM is different from application of hydraulics to achieve the same type of bond in that no expensive high-pressure seals are required with the solid elastomeric material. The bond that is produced with the elastomeric material is not unlike that produced by explosive bonding. However, the bond strength with the elastomeric material is much lower than that achieved by explosive bonding since there is no welding of the two surfaces. The minimum bond strength that is required for any specific application has not been thoroughly investigated, although an initial examination of the bond strength necessary for the machine gun liner has been carried out [de Rosset and Montgomery, 2006].

GLEEM also produces autofrettage in a gun barrel. That is, the application of pressure to the gun tube bore surface produces plastic deformation of the gun tube and a compressive residual stress near the surface that strengthens the gun tube and allows higher operating pressures and a longer fatigue life. The same effect is produced with explosive bonding, although to a higher degree because of the higher pressures. The residual stress produced by GLEEM is a potential problem if lands and grooves need to be machined into the liner.

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The GLEEM process was developed through a combined effort of experimental and computational modeling. Initial experiments involved 4-inch long steel cylinders. Once the basic techniques were ironed out, work proceeded with 12-inch long tubes.

2. THE GLEEM PROCESS

Figure 1 is a schematic of the basic setup for the GLEEM process. The object in the upper left corner of this figure is the item to be lined, generally a thick-walled steel gun tube capable of withstanding high pressure. To the right is a sectional view of the liner, gun tube, and the parts necessary to apply the GLEEM process. In preparation for liner emplacement, the gun tube must be reamed to the appropriate inner diameter. In some instances, it might be necessary to roughen the inner bore of the gun tube in order to increase the mechanical interference between the liner and gun tube and consequently increase the bond strength.

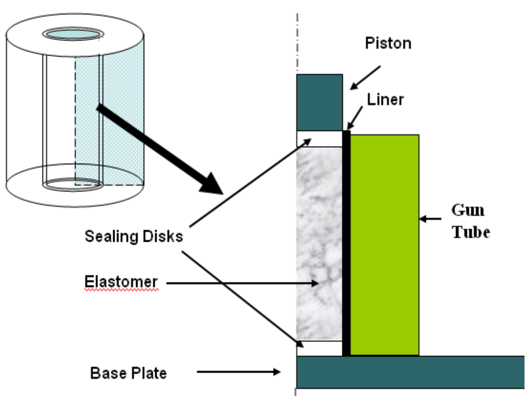

Figure 1. Schematic of GLEEM application setup

Into this gun tube is slipped a thin-walled tube of the selected liner material. Since this tube will be expanded to contact the gun tube, the only tolerances on the outer diameter of the liner tube are such that there is no binding between the gun tube and liner as the liner is put into place. This simplifies the manufacturing of the liner and gun tube; precise tolerances are not necessary. In most instances, the liner outer diameter is 0.002 in to 0.003 in less than the gun tube inner diameter. However, for very long gun tubes where there is the possibility for variation in the inner bore diameter and deviation of the gun tube center line from a straight line, the tolerances on the liner tube might be relaxed. The thickness of the liner must take into account whether lands and grooves will be machined into the liner. After the GLEEM process is applied to the liner, final machining will be performed to achieve the required inner bore diameter for the gun. Choice of initial liner thickness must therefore take into account some radial expansion of the liner and gun tube. In an actual manufacturing process, the liner may be longer than the gun tube, depending on whether a blank or near-net-shape gun tube is being lined.

The elastomeric material is any suitable elastic polymer with a high (~0.5) Poissons ratio. For this particular work, Dow Corning Silastic® J RTV was chosen. This material is made by combining 10 parts of a liquid base with one part of a hardening agent to produce viscous liquid that sets up in 24 hours. The viscous liquid is poured into the liner and allowed to gel into a solid plug of material. The elastomeric plug is made such that it is slightly shorter than the liner. The assembly is cooled in a freezer at -22°F to allow shrinkage of the plug and its removal from the liner. A lubricating material is then applied to the plug, which is then cooled and re-inserted into the liner. If not already in place, the liner is inserted into the gun tube.

Sealing disks made of Nylon™ are then placed inside ends of the liner. The assembly is mounted on a base plate and put into a device capable of applying pressure to one of the disks through a piston. The load frame used in this work was an MTS test machine. After the maximum load for bonding has been achieved, the assembly is removed from the pressure device. Cooling the assembly facilitates the removal of the elastomeric material.

To calculate the internal pressures generated from the GLEEM process, an elasticity analysis is used to derive the relation from axial force and displacement to internal pressure [Carter, 2006]. By using Hooke's law expression for axial strain ε_z for cylindrical coordinates,

$$\varepsilon_z = \frac{1}{E}\left[\sigma_z - \nu(\sigma_r + \sigma_\theta)\right] \qquad (1)$$

and the following relations: $\sigma_r = -P_i$, and $\sigma_r = \sigma_\theta$, for solid cylinders under compression, the expression can be rearranged to :

$$P_i = \frac{E\varepsilon_z - \sigma_z}{2\nu}. \quad (2)$$

In these expressions, P_i is the internal pressure, E is the Young's modulus for the elastomer, ν is the Poisson's ratio, σ is a stress component, and r, θ, and z refer to the radial, hoop, and axial directions, respectively. Since high pressures (>500MPa) will be necessary to plastically deform the liner and gun tube, the Young's modulus for the elastomer is low (5.7 MPa), and the Poisson's ratio is nearly 0.5, the equation can be simplified further:

$$P_i \cong -\sigma_z. \quad (3)$$

This is indicative of the material being forced into a state of hydrostatic compression.

3. DEVELOPMENTAL TESTS

Several tests were conducted using a copper liner inside a 4-in long 4340 steel cylinder. The steel cylinder had an outer diameter of 3 inches and an inner diameter of 1 inch. An MTS load frame was used for pressing the elastomeric material; its maximum capacity is 100000 lbs. Several lessons were learned from these initial tests:

1) The nylon seals must be closely fitted to the liner.
2.) A high-pressure lubricant needs to be used between the liner and elastomer to allow pressure equalization along the tube length. Friction creates axial load transfer from the plug to the liner and results in a pressure gradient along the length of the tube.
3) A retaining ring must be used to keep the base plate and gun tube together (see Figure 2).
4) Time must be allowed for the elastomer to relax and equalize the pressure in the tube.

Since the friction can not be completely removed there will be some pressure gradient in the tube, but the viscoelastic nature of the Silastic® allows for stress relaxation to remove the gradient.

After the GLEEM process had been applied to the copper liner, the shear strength of the bond between the liner and steel tube was measured by a push-out test [de Rosset, et al., 2006]. The experimental arrangement for this measurement is shown in Figure 3. The first step is to section a slice of the steel tube and liner from the sample. A hardened steel pusher plug is then used to push the copper liner out of the sectioned tube. It was found that the bond strength varied somewhat, depending on where the section was taken from the tube. The maximum bond strength generally occurred half way between the top and bottom of the steel tube, corresponding to the area of maximum pressure. Bond strengths between the copper liner and steel tube were measured to be approximately 800 psi for the initial GLEEM applications. This bond strength was improved to over 3500 psi in later tests of longer tubes using the lessons learned in the preceding paragraph.

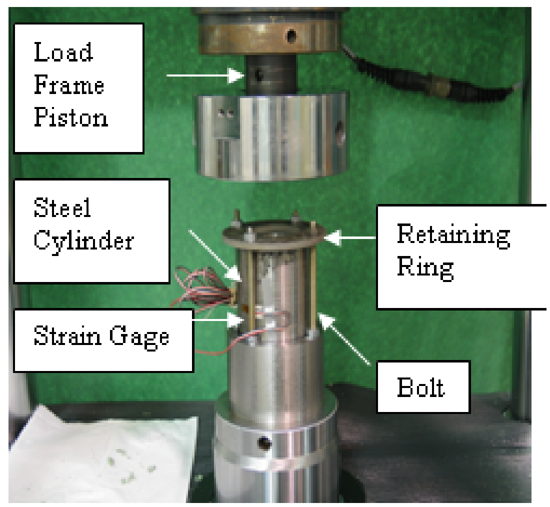

Figure 2. GLEEM Experimental Arrangement

The next liner material examined was Stellite 25. The same arrangement as shown in Figure 2 was used in the GLEEM process. Bond strengths of over 1600 psi were achieved.

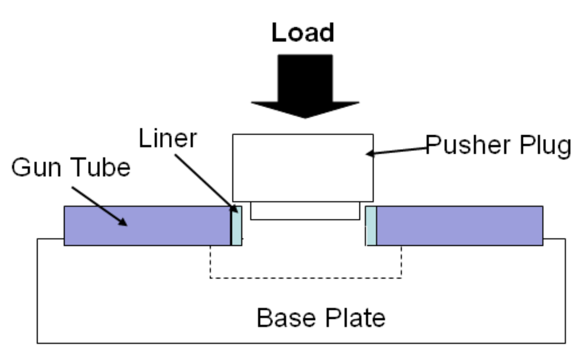

Figure 3. Cross-section of push-out test arrangement

In order to determine the maximum load possible with this arrangement, a Stellite-lined steel tube was made using a higher-strength steel cylinder. Previous steel tubes had a hardness of HRC 17. This particular steel tube was heat treated to a hardness of HRC 34. Care was taken to make the seals as tight-fitting as possible. A million-pound load frame was used to apply pressure to the test arrangement. At a load of 158,749 lbs the seals failed with a loud pop. The radius of the elastomeric plug was 0.42 in, so the calculated pressure was 301.3 ksi. Extensive plastic deformation of the steel cylinder was observed.

The third liner material examined with the GLEEM process was pure tantalum. An 11-in tube was produced by the cold-spray process [Champagne, 2007]. The outer diameter was 0.925 in and the wall thickness varied from 0.091 to 0.092 in. The cold-spry process leaves the material in a hardened condition, and consequently the tantalum tube had to be annealed. The tube was sent to H. C. Starck where it was annealed at 1400°C for 90 minutes in a vacuum (10^{-6} Torr) furnace. Unfortunately, the heat treatment process resulted in two hairline cracks the length of the tube.

It was decided to try to bond a short section of the tube. A 4-in section of the tube was cut from the sample and used in the GLEEM process. The load was taken to 90,000 lbs and the piston displacement held constant. After three minutes, the load had dropped due to the relaxation of the elastomer. Consequently, the load was reset to 90,000 lbs. This procedure was done ten times. At the end of each cycle, the load drop decreased. After the tenth cycle, the displacement was held constant, and the load decreased a small amount over the next hour. Thus, the load cycling appeared to accelerate the achievement of a steady-state load.

When the steel cylinder with tantalum liner was removed from the load frame, it was observed that the fractures in the tantalum had opened up. In trying to make samples for the bond strength tests, the liner shifted inside the steel cylinder, indicating that there was no bond. The final measured inner diameter of the liner was 0.768 in, representing a 3.7% plastic strain in the tantalum had it remained intact.

The GLEEM process was scaled up to 12-in long cylinders and liners. As before, the initial tests were done with copper liners. Hoop strain gages were mounted 4, 6, and 10 inches from the top of the steel cylinder. Loads in the upper range of the MTS load frame were used to press the elastomeric material. The same ten-cycle procedure that was used for the tantalum-lined cylinder was used here.

The outputs from the strain gages located 6 and 10 inches from the top of the steel cylinder are shown in Figure 4. Several observations can be made from these plots:

1) Hoop strain decreases as the distance from the piston increases.
2) Hoop strains measured at both locations reach 85% of the final value very quickly.
3) Cycling the load seems to speed the process.

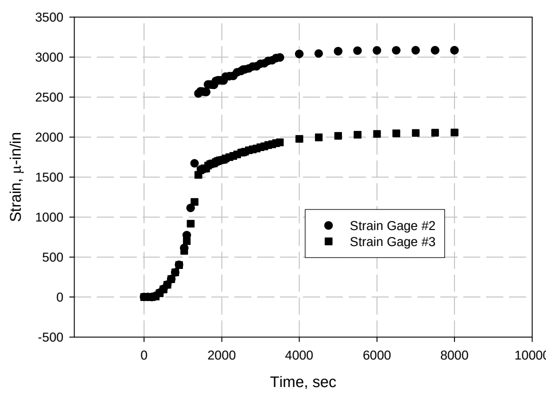

Figure 4. Comparison of hoop strains at 4 inches (#2) and 6 inches (#3) from the top of the steel cylinder

Bond strengths were measured at various locations as described above. Note that the load frame piston was displaced approximately 2 inches into the steel cylinder at the maximum load. This will cause both the hoop strain and bond strength to increase rapidly from the top of the cylinder to a location near the end of the piston. The bond strength results for one of the 12-in tubes are shown below. The decrease in both the strain measurements and the bond strength measurements past the end of the piston indicates that the friction between the elastomeric material and the liner has not been totally eliminated. In effect, a graded autofrettage has been achieved. A graded autofrettage might also be achieved by applying the GLEEM process sequentially to different portions of the tube.

Table 1. Bond Strengths of 12-in Tube

Axial Position (in)	Maximum Load (lbs)	Calculated Bond Strength (psi)
3.9	2541	3580
5.8	2663	3660
9.9	1517	2090

4. MODELING

In order to gain an understanding of the GLEEM process there have been numerous modeling approaches, from elasticity solutions to implicit finite element analyses. The analytical solutions calculate the effectiveness of the rubber plug as the pressurizing media (as shown in Equations 1-3), whereas the FEA efforts simulate the material response and final stress states in the liner and gun tube.

If the edge effects and frictional load transfer are neglected, axisymmetry imposed, and only the elastic-plastic responses of the different materials are represented, a 1-D analysis will be sufficient to model the behavior of the process. In this model, a small number of elements would represent the response of a frictionless section of the composite tube near the middle of the gage section.

Using the ANSYS finite element software, a single row of elements was used to represent the liner and gun tube materials. The model consisted of 56 2-D eight-node elements (PLANE82). Both of the materials were modeled using bilinear kinematic hardening, therefore requiring Young's modulus, yield strength, plastic modulus, and Poisson's ratio to represent the behavior of the materials. The geometry of the model is in Table 2 and the material properties are in Table 3. For the first series of experiments, a Stellite liner was emplaced within an annealed steel tube. The values for the yield point and plastic modulus were estimated to provide good correlation between the model and experimental results. Figure 5 contains a plot of the strain on the outer surface of the jacket versus the internal pressure for the experimental results as well as a series of curves for the FEA simulations.

The bond that is used to hold the liner in place is the friction between the liner and jacket, and not from a metallurgical or chemical bond.

Table 2. Model Dimensions

	Liner	Jacket
Inner Radius (cm)	1.04	1.27
Outer Radius (cm)	1.26	3.77

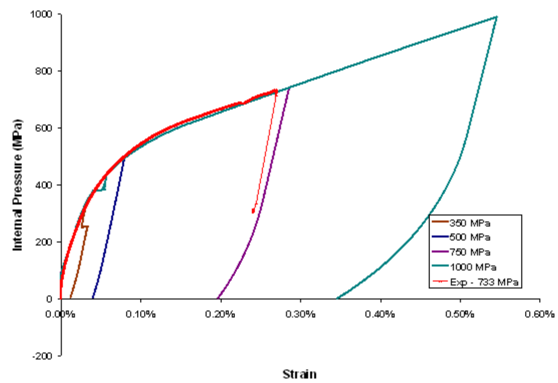

Figure 5. Experimental and FEA simulation results for Stellite liner emplacement in an annealed steel jacket. The graph is the internal pressure versus hoop strain on the outer surface of the jacket.

Efforts are underway to generate more accurate models of the process, capturing the behavior of the plug, role of friction between the plug and liner, and edge effects.

Table 3. Material Properties

Property	Stellite Liner	Copper Liner	Tantalum Liner	Annealed Steel Jacket	Heat Treated Steel Jacket
Elastic Modulus	207 GPa	110 GPa	200 GPa	200 GPa	200 GPa
Yield Stress	400 MPa	300 MPa	400 MPa	350 MPa	1100 MPa
Poisson's Ratio	0.28	0.3	0.28	0.29	0.29
Plastic Modulus	5 GPa	1.17 GPa	5 GPa	20 GPa	20 GPa

5. SUMMARY

A patent has been applied for a process that allows the emplacement of protective liners in gun tubes. It is a relatively inexpensive process and has the potential for extending gun tube life by a significant degree. The term GLEEM has been coined for this process, which involves pressurizing an elastomeric material inside the liner while it is in the gun tube. The pressure plastically deforms the gun tube, setting up residual stresses that bond the liner to the tube. The same stresses represent some degree of autofrettage in the gun tube. Initial developmental tests used copper, tantalum, and Stellite 25 as liner materials and 4340 for the steel gun tube. A finite element computer code was used to model this process, under the assumptions of elastic-perfectly plastic deformation of the materials. Additional modeling and experimental work is planned to explore the limits of the process.

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